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Interactions Among Dietary Fat, Mineral Status, and Performance of Endurance Athletes: A Case Study

Henry C. Lukaski, William W. Bolonchuk, Leslie M. Klevay, David B. Milne, and Harold H. Sandstead

In a pilot study, performance measures and mineral metabolism were assessed in 3 male endurance cyclists who consumed isoenergetic, isonitrogenous diets for 28-day periods in a randomized, crossover design in which dietary carbohydrate, polyunsaturated, or saturated fat contributed about 50% of daily energy intake. Peak aerobic capacity [62 ml/(kg · min)] was unaffected by diet. Endurance capacity at 70–75% peak aerobic capacity decreased with the polyunsaturated fat diet. Copper retention tended to be positive only with saturated fat. Less iron and zinc were retained (intake – losses), and fecal losses of these minerals increased with the polyunsaturated fat. Blood biochemical measures of trace element nutritional status were unaffected by diet, except serum ferritin, which tended to decrease during consumption of the polyunsaturated fat diet. These preliminary results suggest that diets high in polyunsaturated fat, particularly linoleic acid, impair absorption and utilization of iron and zinc, and possibly magnesium, and may reduce endurance performance.

Key Words: saturated fat, polyunsaturated fat, copper, iron, magnesium, zinc, athletes

Introduction

Competitive athletes frequently manipulate the macronutrient content of their diets to boost performance, particularly in endurance sports. Because increasing dietary carbohydrate promotes accumulation of glycogen in liver and skeletal muscle,

H.C. Lukaski, L.M. Klevay, D.B. Milne are with the U.S. Department of Agriculture, Agricultural Research Service, Grand Forks Human Nutrition Research Center, Grand Forks, ND 58202-9034. W.W. Bolonchuk is with the Department of Health, Physical Education and Recreation at the University of North Dakota, Grand Forks, ND 58202-9034. H.H. Sandstead is with the Department of Preventive Medicine and Community Health at the University of Texas Medical Branch, Galveston, TX 77555. Note: The U.S. Department of Agriculture, Agricultural Research Service, Northern Plains Area, is an equal opportunity/ affirmative action employer and all agency services are available without discrimination. Mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the United States Department of Agriculture and does not imply its approval to the exclusion of other products that may also be suitable.

endurance athletes consume diets containing greater than 50% energy intake as carbohydrate during training and before competition. In contrast, some reports suggest an advantage to increasing dietary fat while reducing carbohydrate intake to heighten endurance performance by augmenting fat oxidation and diminishing carbohydrate oxidation, and thus sparing muscle glycogen (25, 27). The practice of dietary "fat loading" is controversial because performance results are inconsistent, and this regimen limits the intensity of exercise that can be performed during endurance training and competition (8, 31).

Nutritional concerns also restrict the generalized use of fat loading diets. The lack of a standardized dietary regimen (including the type and amount of fat consumed and the duration of the fat loading prior to competition) and the concern about the link between high fat diets and some chronic diseases, hamper the use of this dietary practice (20, 31). Another issue is the possible adverse effect of fat on micronutrient bioavailability. Studies of animals and humans fed diets containing a large proportion of energy as fat report anomalies in the absorption and utilization of some mineral elements (18). Also, the type of fat, saturated versus polyunsaturated, affects mineral metabolism (18). Whether the reported effects of dietary fat or carbohydrate on performance measures are influenced by impaired mineral metabolism or status remains to be elucidated.

We report the results of a pilot study that examines the effects of whole-food diets high in dietary fat, as compared to carbohydrate, and their impact on the physical performance of three trained endurance athletes. Because of the limited number of participants, we report preliminary data on individual responses to differences in the type (saturated vs. polyunsaturated) and amount of dietary fat on mineral excretion, whole body retention of selected mineral elements, and blood biochemical indices of mineral nutritional status as possible independent variables that explain differences in physical performance.

Methods

Three male endurance cyclists, aged 20, 20, and 30 years and weighing 71.0 ± 5.2 kg (mean $\pm$ *SD*) with a body mass index of 21.0 ± 1.1 kg/m^2, were recruited by advertisements in cycling magazines and at the Olympic Training Center. The men were informed of the risks and goals of this study. They gave their written informed consent and agreed to abide by the rules of the Metabolic Unit (MU) of the Center before participating in this study. This investigation was approved by the Institutional Review Board of the University of North Dakota School of Medicine and the USDA Human Study Committee, and was conducted in conformity with the Declaration of Helsinki.

The cyclists lived in the MU, except when riding their own bicycles outdoors to maintain their personal training schedules (>400 miles/week), and ate all of their meals at the Center. Only food and beverages provided by the dietary and nursing staff were permitted. Smoking was not allowed. Descriptions of the MU and its operation are available elsewhere (21).

Diet Composition

Diets were prepared from conventional foods and presented in a 3-day rotating menu (18). The macronutrient composition of the experimental diets (Table 1) was calculated by using standard sources (10, 33). These diets were planned to conform with dietary recommendations for American adults (26). The individual energy requirements were determined by dietary history, usual pattern of physical activity, and adjustments of caloric intake during an initial 2-week equilibration period. Thereafter, energy intakes were held constant, and body weight and composition were maintained within 3% of those at admission. The diets were served daily as three substantial meals and a lighter evening snack.

The high carbohydrate diet had energy distributed as 55% carbohydrate, 15% protein, and 30% fat. The two high fat diets, polyunsaturated and saturated fat, were initially planned with energy distributed as 55% fat, 15% protein, and 30% carbohydrate. The high fat diets were similar in composition except safflower oil margarine, polyunsaturated fat nondairy creamer, and safflower oil were used in the polyunsaturated fat diet. In contrast, butter, saturated fat nondairy creamer, and coconut oil were substituted in the saturated fat diet. In addition, small amounts of jelly and fruit juice were added to the saturated fat diet to compensate for differences in the carbohydrate content of the creamers. Because two of the cyclists expressed concerns initially regarding the composition of the saturated fat diet, the contribution of the dietary saturated fat was reduced to 45% energy intake, and butter oil was substituted for coconut oil; the difference in energy intake was made up with carbohydrate, mainly as fruit juices. The concerns focused on certain diet components and were not related to gastrointestinal disturbances.

After admission, the men ate an equilibration diet that was similar to the typical U.S. diet (15% protein, 45% carbohydrate, and 40% fat) during the first 14 days of the study, then they consumed each experimental diet in a randomized crossover design. The experimental diets were fed for 28-day periods.

Table 1 Calculated Daily Energy and Macronutrient Composition of the Diets

Variable	CHO[a]	PUSF	SATF
Energy (kcal)	5083 ± 382	5083 ± 382	5083 ± 382
Protein (g)	193 ± 15	192 ± 14	197± 16
% energy	15	15	15
Carbohydrate (g)	703 ± 54	385 ± 28	468 ± 85
% energy	55	30	37 ± 6[b]
Fat (g)	171 ± 14	312 ± 23	274 ± 33
% energy	30	55	48 ± 6[c]
Linoleic acid (g/day)	8 ± 0.6	152 ± 11	12 ± 1
Saturated fatty acids (g/day)	90 ± 7	58 ± 5	146 ± 31[b]
Linoleate/SATF	0.09	2.6	0.08 ± 0.02[b]

Note. Values are mean ± *SD*.
[a]CHO = carbohydrate, PUSF = polyunsaturated fat, SATF = saturated fat; [b]Dietary SATF acids contributed 45% energy intake in two cyclists and 55% in another cyclist.

Sample Collections and Chemical Analyses

Excreta and diets were collected with precautions to avoid trace metal contamination. Six-day composites of diets and feces were prepared separately by homogenization in a one-gallon stainless steel blender. Aliquots of the diet and fecal composites were digested with concentrated nitric and 70% perchloric acids by method IIA of the Analytical Methods Committee (1). The zinc, iron, and magnesium contents of the digestates were determined by flame atomic absorption spectrophotometry (AAS) with aqueous calibration standards. Methodological precision and accuracy were evaluated by concurrent analysis of bovine liver standards (NIST, Gaithersberg, MD), pool samples, and replicate samples containing metal. We found 131, 267, and 605 μg per gram of bovine liver standard, as compared with certified values of 130, 270, and 605 μg per gram for zinc, iron, and magnesium, respectively. Within batch precision (coefficient of variation) of replicate diet, pool samples averaged 2.3, 2.8, and 0.9%, whereas batch to batch precision averaged 3.8, 3.3, and 4.4% for zinc, iron, and magnesium, respectively. Within batch precision of the fecal pool, samples averaged 2.5, 3.1, and 2.1%, whereas batch to batch precision averaged 3.2, 3.8, and 3.9% for zinc, iron, and magnesium.

Urinary zinc and iron were measured by direct aspiration of urine into the AAS flame. Urinary magnesium was determined by AAS after dilution in 0.5% lanthanum chloride to mask interferences.

Complete 24-hour urine and fecal collections were made for 12 days, four consecutive 3-day menu rotations, at the end of each dietary period. Chemical balance or retention was calculated as the difference between dietary intake and the sum of fecal and urinary losses, and expressed as daily averages per 12-day balance period. Surface losses of minerals were not determined.

Blood was drawn into plastic syringes from an antecubital vein, which had been distended by temporary use of a tourniquet, after the subjects had fasted for 12 hours. Hemoglobin was determined by using a Coulter hemoglobinometer (Coulter Electronics, Hialeah, FL). We measured the hematocrit by using hematocrit autocrit tubes (Clay Adams, Parsippany, NY). Serum iron was determined by an AAS procedure described by Caraway (6). Ferritin was determined by radioimmunoassay (Calbiochem Behring, La Jolla, CA). Plasma zinc concentrations were determined by AAS after dilution with deionized water. Serum magnesium was analyzed by AAS after dilution with a 0.5% lanthanum chloride solution (4).

Exercise Testing and Performance Measures

Exercise testing was accomplished with a Monark ergocycle (Varberg, Sweden) that was modified with toe clips, drop handle bars, and a racing seat. Peak aerobic capacity was measured after an overnight fast during the final week of each dietary period by using our modification of a progressive, graded, peak exercise protocol for elite cyclists (20). Oxygen consumption was measured every minute during the test with a Beckman Metabolic Measurement Cart (Beckman Instruments, Fullerton, CA).

Endurance capacity was determined on the last day of each dietary period; testing occurred approximately 2 hours after breakfast. Each cyclist pedaled at an external work load of about 50% peak work capacity for 30 min to warm up, then increased work intensity to elicit 70–75% peak work capacity until he could not maintain the required pedaling rate of 80–90 rpm. Endurance was determined by the time to voluntary exhaustion after completion of the warm-up period.

Statistical Methods

Data are presented as mean ± *SD*. Because serum ferritin data are not normally distributed in human populations, the data are log transformed. The effects of dietary treatments on mineral excretion and balance, and blood biochemical measures of mineral nutritional status are expressed as individual responses by dietary treatment.

Results

The cyclists had considerable energy intakes, which are consistent with their high daily energy expenditures associated with their daily training programs (Table 1); energy intakes were constant throughout the 3-month experiment. Mean dietary carbohydrate associated with the three diets ranged from 385 to 703 g/day, whereas fat intake averaged from 171 to 312 g/day. Body weight and composition did not change.

Diet affected one aspect of physical performance (Table 2). Although peak oxygen uptake was similar regardless of dietary treatment, endurance time decreased in each cyclist with the polyunsaturated fat (112 ± 3 min) as compared to the carbohydrate and saturated fat diets (121 ± 5 and 127 ± 4 min, respectively). The range of the decrement was from 3 to 15 min.

The type and amount of dietary fat apparently impacted the metabolism and retention of some mineral elements (Table 3). For two cyclists, copper retention was

Table 2 Effects of Dietary Carbohydrate (CHO), Polyunsaturated (PUSF), and Saturated Fat (SATF) on Peak Oxygen Uptake ($\dot{V}O_{2peak}$) and Endurance Measures in 3 Male Cyclists

Subject	Diet	$\dot{V}O_{2peak}$ [ml/(min · kg)]	Endurance (min)
A	Admit	59.3	114
	CHO	60.0	115
	PUSF	59.4	112
	SATF	59.5	120
B	Admit	57.2	118
	CHO	58.5	122
	PUSF	57.0	115
	SATF	57.6	128
C	Admit	69.3	125
	CHO	68.4	125
	PUSF	69.0	110
	SATF	69.1	131

Table 3 Data by Individual Cyclist (Vol) on Dietary, Fecal, and Urinary Iron, Magnesium, and Zinc Excretions and Balance (Bal) by Diet[a]

		Copper						Iron						Magnesium						Zinc					
	Vol/	Diet	Feces		Urine		Bal	Diet	Feces		Urine		Bal	Diet	Feces		Urine		Bal	Diet	Feces		Urine		
Subject	Diet	mg/d	mg/d	%[b]	mg/d	%	mg/d	mg/d	mg/d	%	mg/d	%	mg/d	mg/d	mg/d	%	mg/d	%	mg/d	mg/d	mg	%	mg/d	%	Bal.
A	CHO	2.8	2.7	98	0.1	3	–0.03	46.6	28.1	61	0.12	0.3	18.5	552	256	47	265	48	29	24.9	20.1	80	1.2	5	3.6
	PUSF	2.6	2.4	98	0.1	2	0.11	46.0	38.9	84	0.13	0.3	7.1	590	351	60	255	43	–16	27.7	26.2	95	1.1	4	0.4
	SATF	2.5	2.4	98	0.1	1	–0.08	50.9	32.1	63	0.11	0.2	18.7	692	380	55	279	40	33	29.0	23.0	79	1.2	4	4.8
B	CHO	3.0	2.4	81	0.1	2	0.60	39.9	30.3	76	0.10	0.2	9.5	480	258	54	179	37	43	21.5	17.6	82	0.8	4	3.2
	PUSF	2.2	2.2	100	0.1	4	–0.14	36.7	39.5	107	0.11	0.3	–2.9	520	379	73	173	33	–32	24.4	24.7	101	0.7	3	–0.9
	SATF	2.3	2.2	98	0.1	1	0.01	42.6	37.1	87	0.10	0.2	5.5	598	384	64	184	32	30	26.7	20.6	77	0.7	3	5.4
C	CHO	2.5	2.3	98	0.1	4	0.10	46.2	32.1	70	0.11	0.2	14.0	522	290	56	198	38	34	25.4	22.4	89	0.5	3	2.4
	PUSF	1.9	1.9	100	0.1	4	–0.15	36.3	35.3	97	0.10	0.3	0.7	522	318	64	196	39	–15	22.9	20.9	91	0.7	3	1.4
	SATF	2.0	1.7	98	0.1	1	0.20	45.3	30.7	67	0.06	0.1	14.8	543	264	49	211	40	68	26.0	17.9	69	0.6	3	7.5

[a]CHO = carbohydrate, PUSF = polyunsaturated fat, SATF = saturated fat; [b]% = loss expressed as a percentage of daily intake.

negative (–0.15 and –0.14 mg/day) when the polyunsaturated diet was consumed; it was positive for one cyclist (0.11 mg/day). Overall, copper balance was positive (0.04 ± 0.1 mg/day) only for the saturated fat compared to the carbohydrate and polyunsaturated (–0.03 ± 0.6 and –0.06 ± 0.1 mg/day, respectively) diets. Magnesium balance was negative (–5 ± 34 mg/day), only with the polyunsaturated fat diet; it was positive and similar to 0 with the carbohydrate and saturated fat diets (19 ± 30 and 44 ± 21 mg/day, respectively).

More consistent responses of diet were observed on whole-body zinc and iron retention (Table 3). Polyunsaturated fat decreased zinc retention or balance (0.6 ± 1.7 mg/day) as compared to the saturated fat (5.9 ± 1.4 mg/day) and the carbohydrate (2.7 ± 1.2 mg/day) diets. Relative zinc losses in the feces increased to 95% of dietary zinc when polyunsaturated fat was consumed; losses were 85% and 75% on the carbohydrate and saturated fat diets, respectively. A small difference in the zinc intake was observed as a result of changes in the foods used to accommodate the changes in carbohydrate and fat composition of the diets. The difference of approximately 5 mg in zinc retention exceeds the difference of 1.5 mg in dietary zinc between the diets high in saturated and polyunsaturated fat.

Iron balance also was reasonably affected by the type of fat consumed (Table 3). Iron retention was markedly decreased in all cyclists when the polyunsaturated fat (1.7 ± 5.0 mg/day) as compared to the carbohydrate and saturated fat diets (14.0 ± 4.5 and 13.0 ± 6.5 mg/day, respectively) was consumed. Because of the remarkable increase in fecal iron excretion, expressed as a percentage of iron intake, polyunsaturated fat (96%) as compared to carbohydrate and saturated fat (69 and 72%, respectively) apparently hampered iron absorption.

The amount of dietary linoleic acid evidently influenced the excretion and retention of some of minerals (Table 4). High dietary linoleate was associated with increased fecal iron and zinc losses, and decreased iron balance (1.7 ± 5.0 vs. 13.5 ± 5.6 mg/day) with some evidence of reduced zinc retention (0.6 ± 1.7 vs. 4.3 ± 0.1 mg/day). Body losses of magnesium (–5 ± 34 vs. 31 ± 5 mg/day) exceeded dietary intakes when dietary linoleate increased from 13 to 140 g/day.

Blood biochemical measures of mineral element nutritional status were within the range of normal values and generally were not affected by differences in dietary fat and carbohydrate (Table 5). The log transformed serum ferritin declined when the high polyunsaturated fat, as compared to carbohydrate and saturated fat, was consumed (4.1 ± 1.1 vs. 4.5 ± 0.9 and 4.3 ± 1.0 μg/L, respectively).

Discussion

This study examined the hypothesis that changes in the macronutrient composition of the diets of endurance athletes affect physical performance measures indirectly by influencing trace element metabolism and apparent utilization. We report that changes in dietary carbohydrate and fat, regardless of type of fat, do not impact peak oxygen uptake. This finding is consistent with the results of another investigation of trained endurance cyclists (27) that failed to identify any effect of alterations in dietary carbohydrate and fat content on peak aerobic capacity; the observed changes (±2–3%) in these studies are consistent with the biological and technical variability of the method.

The effect of dietary carbohydrate and fat on endurance performance also is unsettled. Studies (2, 7, 10, 28) of endurance-trained athletes showed significant

Table 4 Effects of Graded Linoleate Intake on Excretion and Balance of Selected Minerals in 3 Cyclists

Mineral	Linoleate (g/d)	Diet (mg/d)	Feces (mg/d)	%[a]	Urine (mg/d)	%	Balance (mg/d)
Iron	Low[b]	45.3 ± 3.8	31.7 ± 1.8	70 ± 10	0.10 ± 0.02	1 ± 1	13.5 ± 5.6
	High	39.7 ± 5.5	37.9 ± 2.3	96 ± 113	0.10 ± 0.03	1 ± 1	1.7 ± 5.0
Magnesium	Low	560 ± 54	310 ± 17	55 ± 4	219 ± 47	39 ± 5	31 ± 5
	High	544 ± 39	340 ± 45	63 ± 9	209 ± 42	38 ± 5	−5 ± 34
Zinc	Low	25.2 ± 1.6	20.1 ± 1.4	80 ± 1	0.87 ± 0.31	4 ± 1	4.3 ± 0.1
	High	25.8 ± 1.7	24.4 ± 1.9	95 ± 6	0.76 ± 0.29	3 ± 1	0.6 ± 1.7

Note. Values are mean ± *SD*.
[a]Loss expressed as a percent of daily intake; [b]Low ≤ 13 g/d; high ≥ 140 g/d.

Table 5 Blood Biochemical Indices of Iron, Zinc, and Magnesium Nutriture at Entry and in Response to Diets High in Carbohydrate (CHO), Polyunsaturated (PUSF), and Saturated (SATF) Fat in 3 Male Endurance Cyclists (Vol)

Subject	Vol/diet	Hematocrit (%)	Hemoglobin (g/L)	Serum Ferritin (μg/L)	Serum Iron (μmol/L)	Serum Magnesium (mmol/L)	Plasma Zinc (μmol/L)
A	Entry	43	146	200	44	0.87	16.1
	CHO	42	140	185	46	0.91	13.5
	PUSF	40	138	138	45	1.03	12.1
	SATF	43	151	179	43	0.99	15.0
B	Entry	44	151	140	27	0.87	14.2
	CHO	41	140	101	22	0.91	12.5
	PUSF	43	146	97	27	0.91	12.1
	SATF	43	150	83	22	0.91	12.5
C	Entry	43	138	28	22	0.99	12.9
	CHO	42	142	34	25	0.99	12.9
	PUSF	41	140	17	12	1.03	10.9
	SATF	43	134	26	32	0.99	14.7

increases in endurance performance at 70–75% peak aerobic capacity, with diets containing dietary carbohydrate ranging from 77–83 % and corresponding dietary fat ranging from 10–64 % of energy intakes, and dietary adaptation periods of 3–14 days. Although more recent work (30) with trained athletes consuming a high carbohydrate diet (72%) confirms improved endurance performance (7–15%) as compared to a high fat diet (43%), other studies indicate no improvement in performance (29).

The mechanism of the enhancement of endurance performance by high fat diets apparently relates to an adaptation in fat metabolism. High fat diets increase fat oxidation by increasing both the capacity for fatty acid transport and oxidation in muscle during endurance exercise (8, 16). This functional adaptation is characteristic of highly trained endurance athletes because untrained subjects fail to increase endurance performance when a high fat diet (62%) is fed (10, 12).

The inconsistent findings in previous studies (7, 30) may be explained by differences in experimental designs. Factors such as variation in diet composition (i.e., proportions of carbohydrate and fat), duration of adaptation to each experimental diet and type of endurance exercise (laboratory test vs. field performance test) may have contributed to the lack of consensus.

A key variable uncontrolled in previous investigations was the composition of the fat diet (i.e., the fatty acid composition of the fat diets). The present study addresses this concern by using diets high in fat that differ in their polyunsaturated versus saturated fat contents (Table 1), and reports decreased endurance performance with polyunsaturated fat.

The apparent change in endurance capacity may be related to the effect of dietary fat on mineral metabolism. Rats fed diets high in fat (>25%) exhibited adverse effects on magnesium, iron, and zinc status (18). Polyunsaturated fat intake was associated with decreased magnesium absorption (15). Safflower oil, as compared to coconut oil, decreased the absorption and retention of zinc and reduced liver concentrations of zinc (22). Linoleic acid fed at 2.5%, as compared to 0.8%, resulted in significantly decreased serum and tibial zinc, and decreased high-density lipoprotein cholesterol (17). Thus, polyunsaturated fat apparently decreases the absorption and utilization of zinc, and the distribution of zinc in some body tissues.

The interaction between dietary fat and iron has been examined in animals and humans. Iron-deficient rats fed lard at 20% compared to 5% exhibited increased iron absorption when dietary iron was provided as ferrous sulfate, rather than heme iron, at low as compared to adequate amounts (3). Factorial studies of the effects of amount of dietary iron (10 vs. 35 mg/kg diet), amount (5 vs. 35%) and type of fat (safflower vs. coconut oil) demonstrated that saturated fat enhanced iron utilization, particularly hemoglobin regeneration, in iron-deficient rats (14). In a study of 12 men fed a diet containing 42% fat, increasing linoleate from 4 to16% resulted in a significant decrease in iron balance and a decline in hemoglobin and hematocrit (34). These findings indicate that, as compared to saturated fat, polyunsaturated fat, particularly linoleic acid, diminishes iron absorption and utilization in animals and humans.

Recent evidence suggests that a specific saturated fatty acid may be responsible for increasing non-heme iron absorption. Anemic animals fed beef fat, compared to turkey fat, corn oil, or pork fat, were most efficient at converting turkey meat into hemoglobin (23). Beef fat, however, contains almost 19% stearic acid, which is 10 times the stearic acid content of corn oil, 3 times the content of turkey fat, and 1.5 times that of lard. The hypothesis that stearic acid improves iron utilization was tested in anemic rats fed graded amounts of stearic acid and safflower oil and different amounts of iron as ferrous sulfate (14). Compared to safflower oil, stearic acid significantly enhanced repletion of hemoglobin, hematocrit, and liver iron; this beneficial effect was greatest when dietary iron was low.

In the present study, evidence of altered mineral metabolism was found (Table 3). Polyunsaturated fat, as compared to saturated fat and carbohydrate, was associated with significant losses of iron and zinc as well as a tendency for magnesium loss. Increases in fecal losses of these minerals occurred when polyunsaturated fat was fed. Importantly, these adverse effects were found when dietary linoleic acid was high (≥140 mg/day; Table 4). These findings are consistent with results from previous studies of animals and humans fed diets containing predominantly polyunsaturated fat or linoleic acid (18). Furthermore, the increased fecal mineral output is consistent with findings of decreased iron and zinc absorption using radioisotopes in animals (18).

Despite these effects on mineral excretion and retention, there was limited evidence of any detrimental impact on blood biochemical measures of mineral nutritional status. This observation may be explained by the limited duration (28 days) during which the high fat diets were fed. In general, prolonged periods of either low dietary intake or presence of food components that inhibit absorption and utilization of the essential mineral element are needed to produce biologically significant decreases in blood biochemical measures of mineral nutritional status in adult humans (21, 24). Body iron stores, as indexed by serum ferritin, declined. Because reduction in serum ferritin is an indicator of decreased body iron stores, it is plausible that prolonged consumption (>28 days) of a diet high in polyunsaturated fat may promote the depletion of tissue iron stores and increase the potential for impairments in endurance training and performance.

Consumption of high-fat compared to high-carbohydrate diets for periods exceeding 28 days is associated with decreased endurance performance (11, 12) despite up-regulation of fatty acid oxidative capacity. Some putative mechanisms, including increased sympathetic activity, altered membrane fluidity and decreased exercise-induce glucose uptake, have been proposed to explain the decrement in performance with prolonged (>4 weeks) consumption of a high-fat diet (16). The results of the present study suggest that consumption of large amounts of polyunsaturated fatty acids (>140 g/day) may be another tenable hypothesis because polyunsaturated fat apparently inhibits absorption and facilitates excretion of some mineral elements, particularly iron, with a tendency to decrease body iron stores.

While prolonged consumption of diets is required to induce changes in mineral metabolism and redistribution of minerals in physiological pools (e.g., soft tissue), shorter durations of consumption to diets high in fat and carbohydrate elicit adaptations in metabolism. For example, consumption of a diet high in carbohydrate for 7 days promotes muscle glycogen loading, whereas 5 to 10 days are needed for muscle adaptation to a high fat diet particularly during endurance exercise training (5, 9, 27, 31).

The findings of the present study extend to humans the previous reports in animals of an inhibitory effect of diets high in polyunsaturated fat, particularly linoleic acid, on mineral bioavailability, specifically iron, zinc, and possibly magnesium (18). Because of the important roles that these minerals play in the regulation of energy metabolism and integration of many physiological processes (19), consumption of diets containing large amounts of polyunsaturated fat and linoleic acid is not recommended. Also, the apparent augmentation of endurance performance with consumption of the saturated fat diet should be viewed cautiously. As compared to the polyunsaturated fat diet, the 12% boost in endurance performance with the saturated fat diet was more than two times greater (5%) than that seen with the carbohydrate diet. Because saturated fat increases total serum cholesterol and low density lipoprotein cholesterol independently of activity level (20), consumption of the saturated fat diet for prolonged durations (>28 days) is not recommended.

In summary, our findings indicate that consumption of a diet high in polyunsaturated fat impairs endurance performance as compared to isocaloric, isonitrogenous diets high in either carbohydrate or saturated fat. The polyunsaturated fat was associated with reduced retention of iron and zinc in the body, and the reduction of body iron stores. We recognize that the limited number of subjects may restrict the extension of our performance findings to all endurance athletes. Thus, additional studies are needed to confirm the apparent adverse interaction between polyunsaturated fat, specifically linoleic acid, and endurance performance mediated by altered mineral metabolism. Also, the use of the chemical balance method only provides an indication of relative changes in body accumulation or loss of minerals. It also should be noted that the diet high in carbohydrate provided carbohydrate in an amount (55% energy intake) that may be considered usual for most endurance performers. Thus, the apparent adverse effect of high polyunsaturated fat might best be assessed relative to the saturated fat diet.

References

1. Analytical Methods Committee. Methods of destruction of organic material. *Analyst* 85:643-656, 1960.
2. Bergstrom, J., L. Hermansen, E. Hultman, and B. Saltin. Diet, muscle glycogen and physical performance. *Acta Physiol. Scand.* 71:140-150, 1967.
3. Bowering, J., G.A. Masch, and A.R. Lewis. Enhancement of iron absorption in iron depleted rats by increasing dietary fat. *J. Nutr.* 107:1687-1693, 1977.
4. Bowers, G.N., and J. Pybus. Total calcium in serum by atomic absorption spectrophotometry. In: *Standard methods of clinical chemistry*, Vol. 7, S. Meites (Ed). New York: Academic Press, 1972, p. 143.
5. Burke L.M., D.J. Angus, G.R. Cox, N.K. Cummings, M.A. Febbraio, K. Gawthorn, J.A. Hawley, M. Minehan, D.T. Martin, and M. Hargreaves. Effect of fat adaptation and carbohydrate restoration on metabolism and performance during prolonged cycling. *J. Appl. Physiol.* 89:2413-2421, 2000.
6. Caraway, W.T. Macro and micro methods for the determination of serum iron and iron-binding-capacity. *Clin. Chem.* 9:188-199, 1963.
7. Coyle, E.F., and B.J. Hodgkinson. Influence of dietary fat and carbohydrate on metabolic and performance responses. In: *Perspectives in Exercise Science and Sports Medicine: Volume 12. The Metabolic Bases of Exercise and Sports Performance,* D.R. Lamb, L. Spriet and R. Murray (Eds.). Carmel, IN: Benchmark, 1999, pp. 165-206.
8. Galbo, H., J.J. Holst, and N.T. Christensen. The effect of different diets and of insulin on the hormonal response to prolonged exercise. *Acta Physiol. Scand.* 107:19-32, 1979.
9. Goedecke J.H., C. Christie, G. Wilson, S.C. Dennis, T.D. Noakes, W.G. Hopkins, E.V. Lambert. Metabolic adaptations to a high fat diet in endurance cyclists. *Metabolism* 48:1509-1517, 1999.
10. Hardinge, M.D., J.B. Swarner, and H. Crooks. Carbohydrates in foods. *J. Amer. Diet. Assoc.* 46:197-204, 1965.
11. Helge, J.W., E.A. Richter, and B. Kiens. Interaction of training and diet on metabolism and endurance during exercise in man. *J. Physiol.* 492:293-306, 1996.
12. Helge, J.W., B. Wulff, and B. Kiens. Impact of a fat-rich diet on endurance in man: role of dietary period. *Med. Sci. Sports Exerc.* 30:456-461, 1998.
13. Johnson, P.E., H.C. Lukaski, and T.D. Bowman. Effects of level and saturation of fat and iron level and type in the diet on iron absorption and utilization by the rat. *J. Nutr.* 117:501-507, 1987.

14. Johnson, P.E., H.C. Lukaski, and E.D. Korynta. The effects of stearic acid and beef tallow on iron utilization by the rat. *Proc. Soc. Exp. Biol. Med.* 200:480-486, 1992.
15. Kaup, S.M., A.R. Behling, L. Choquette, and J.L. Greger. Calcium and magnesium utilization in rats: effect of dietary butterfat and calcium and of age. *J. Nutr.* 120:266-273, 1990.
16. Kiens, B., and J.W. Helge. Effect of high-fat diets on exercise performance. *Proc. Nutr. Soc.* 57:73-75, 1998.
17. Koo, S.I., and J.S. Ramlet. Effect of dietary linoleic acid on the tissue levels of zinc and copper, and serum high-density lipoprotein cholesterol. *Atherosclerosis* 50:123-132, 1984.
18. Lukaski, H.C. Dietary fatty acids and minerals. In: *Fatty Acids in Foods and Their Health Implications*, 2nd ed., C.K. Chow (Ed.). New York: Marcel Dekker, 1999, pp. 541-555.
19. Lukaski, H.C. Vitamin and mineral metabolism and exercise performance. In: *Perspectives in Exercise Science and Sports Medicine: Volume 12. The Metabolic Bases of Exercise and Sports Performance,* D.R. Lamb, L. Spriet, and R. Murray (Eds.). Carmel, IN: Benchmark, 1999, pp. 261-314.
20. Lukaski, H.C., W.W. Bolonchuk, L.M. Klevay, J.R. Mahalko, D.B. Milne, and H.H. Sandstead. Influence of type and amount of dietary lipid on plasma lipid concentrations in endurance athletes. *Am. J. Clin. Nutr.* 39:35-44, 1984.
21. Lukaski, H.C., L.M. Klevay, and D.B. Milne. Effect of dietary copper and ascorbic acid on human autonomic cardiovascular function. *Eur. J. Appl. Physiol.* 58:74-80, 1988.
22. Lukaski, H.C., G.I. Lykken, and L.M. Klevay. Simultaneous determination of copper, iron and zinc absorption using gamma ray spectroscopy: fat effects. *Nutr. Rep. Int.* 33:139-146, 1986.
23. Mahoney, A.W., B.R. Farmer, and D.G. Hendricks. Effects of level and source of dietary fat on the bioavailability of iron from turkey meat for the anemic rat. *J. Nutr.* 110:1703-1708, 1980.
24. Milne, D.B., S.K. Gallagher, and F.H. Nielsen. Response of various indices of iron status to acute iron depletion by low iron intake and phlebotomy in menstruating women. *Clin. Chem.* 36:487-491, 1990.
25. Muoio, D.M., J.J. Leddy, P.J. Horvath, A.B. Awad, and D.R. Pendergast. Effect of dietary fat on metabolic adjustments to maximal **V**O$_2$ and endurance in runners. *Med. Sci. Sports Exerc.* 26:81-88, 1994.
26. National Research Council. *Recommended Dietary Allowances*, 10th ed. Washington, DC: National Academy Press, 1989.
27. Phinney, S.D., B.R. Bistrian, W.J. Evans, E. Gervino, and G.L. Blackburn. The human metabolic response to chronic ketosis without caloric restriction: preservation of submaximal exercise capacity capability with reduced carbohydrate oxidation. *Metabolism* 32:769-776, 1983.
28. Pruett, E.D.R. Glucose and insulin during prolonged work stress in men living on different diets. *J. Appl. Physiol.* 28:199-208, 1970.
29. Sherman, W.M., J.A. Doyle, D.R. Lamb, and R.H. Strauss. Dietary carbohydrate, muscle glycogen and exercise performance during 7-d of training. *Am. J. Clin. Nutr.* 57:27-31, 1993.
30. Sherman, W.M., and D.R. Lamb. Nutrition and prolonged exercise. In: *Perspectives in Exercise Science and Sports Medicine: Volume 1. Prolonged Exercise,* D.R. Lamb and R. Murray (Eds.). Carmel, IN: Benchmark, 1988, pp. 213-280.

31. Sherman, W.M., and N. Leenders. Fat loading: the next magical bullet? *Int. J. Sports Nutr.* 5:S1-S12, 1995.
32. Simonsen, J.C., W.M.. Sherman, D.R. Lamb, A.R. Dernbach, J.A. Doyle, and R. Strauss. Dietary carbohydrate, muscle glycogen, and power output during rowing training. *J. Appl. Physiol.* 70:1500-1505, 1991.
33. U.S. Department of Agriculture, Consumer and Food Economics Institute. *Food Composition Data Set No. 456-3.* Hyattsville, MD, 1977.
34. Van Dokkum, W., F.A. Cloughley, K.F.A.M. Hulsof, and L.A.M. Osterveen. Effect of variations in fat and linoleic acid on the calcium, magnesium and iron balances of young men. *Ann. Nutr. Metab.* 27:361-369, 1983.

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